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Perspectives

The US National Nanotechnology Initiative after 3 years (2001–2003)

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Abstract

Research and education results after the first 3 years of National Nanotechnology Initiative (NNI) investment are outlined. The history of NNI and several potential outcomes by 2015 are discussed. The views expressed here are based on the interview given for the website www.nano.gov on November 2003.

What is the National Nanotechnology Initiative?

The National Nanotechnology Initiative (NNI) is a visionary research and development program that coordinates 16 departments and independent agencies, with a total investment of about $961 million in fiscal year (FY) 2004. The program started formally in FY 2001 (October 2000), and was the result of a bottom-up activity proposing the idea of developing nanoscale science and engineering that got started in 1996. The Federal nanotechnology investment per agency since the beginning of NNI is given in Table 1. The main goals of NNI are as follows:

- to extend the frontiers of nanoscale science and engineering though support for research and development;
- to establish a balanced and flexible infrastructure, including a skilled workforce;
- to address the societal implications of nanotechnology, including actions and anticipatory measures that should be undertaken in the society to bring sooner the advantage of the new technology and in a responsible way; and
- to establish a grand coalition of academe, industry and government to realize the full potential of the new technology.

Indeed, nanotechnology's shift in focus from the microscale to the molecular and nanoscale will be essential for future advances in both the digital revolution and modern biology – and may change the very foundation of education, medicine, manufacturing, and the environment. Initially, NNI was driven by science as outlined in 'Nanotechnology Research Directions' (Roco et al., 1999), but after 2002, technological innovation has risen in importance. Industry has become a strong supporter and its long-term R&D nanotechnology investment is expected to surpass the Federal NNI expenditures next year. Also, over 20 states in US have realized that nanotech has economic potential and in 2002 made a commitment for nanotechnology that is more than half the NNI annual budget. The 2003 worldwide government investment in nanotechnology in part stimulated by NNI was about $3 billion, a sevenfold increase as compared to about $430 million in 1997 (Table 2). Nanotechnology is expanding in a natural and robust way. We are creating the systematic control of matter at the nanoscale. We have clear research and education needs in the national and international context. The White House and Congress have recognized the importance of nanotechnology in the future of US through the 'NNI-Supplement to the President's FY 2004 Budget' (NSTC, 2003) and '21st Century Nanotechnology Research and Development Act' (US Congress, 2003). NNI, in

Table 1. Contribution of key Federal departments and agencies to NNI investment in $ million/year (each FY begins on October 1 of the previous year and end on September 30 of the respective year)

Federal Department or Agency	Actual ($M)				FY 2004 Enacted ($M)
	FY 2000	FY 2001	FY 2002	FY 2003	
National Science Foundation (NSF)	97	150	204	221	254
Department of Defense (DOD)	70	125	224	322	315
Department of Energy (DOE)	58	88	89	134	203
National Institutes of Health (NIH)	32	40	59	78	80
National Institute of Standards and Technology (NIST)	8	33	77	64	63
National Aeronautics and Space Administration (NASA)	5	22	35	36	37
Environmental Protection Agency (EPA)	—	6	6	5	5
Homeland Security (TSA)	—	—	2	1	1
Department of Agriculture (USDA)	—	1.5	0	1	1
Department of Justice (DOJ)	—	1.4	1	1	2
Total	270	465	697	862	961
(% of 2000)	(100%)	(172%)	(258%)	(319%)	(356%)

Table 2. Estimated government nanotechnology R&D expenditures in 1997–2003 in $ millions/year (estimations made at NSF)

Region	1997	1998	1999	2000	2001	2002	2003	2004***
W. Europe	126	151	179	200	~225	~400	~650	~900
Japan	120	135	157	245	~465	~720	~800	~900
USA*	116	190	255	270	465**	697**	862**	960
Others	70	83	96	110	~380	~550	~800	~900
Total	432	559	687	825	1535	2367	3122	3660
(% of 1997)	(100%)	(129%)	(159%)	(191%)	(355%)	(547%)	(722%)	(847%)

'W. Europe' includes countries in EU and Switzerland; the rate of exchange $1 = 1.1 Euro until 2002; = 0.9 Euro in 2003; and = 0.8 Euro in 2004; Japan rate of exchange $1 = 120 yen until 2002; = 110 yen in 2003; and = 105 yen in 2004; 'Others' include Australia, Canada, China, Eastern Europe, FSU, Israel, Korea, Singapore, Taiwan and other countries with nanotechnology R&D.

*A financial year begins in USA on October 1 of the previous calendar year, 6 months before in most other countries.

**Denotes the actual budget recorded at the end of the respective FY. Estimates use the nanotechnology definition as defined in the NNI (this definition does not include MEMS), and include the publicly reported government spending.

***Denotes preliminary data.

collaboration with other worldwide nanotechnology programs, has the potential to bring broad societal changes from increasing the productivity to extending the quality of life and the sustainability limits on Earth for a population exceeding 6 billion.

How did the idea of a multiagency NNI begin to emerge?

Participation of multiple agencies is necessary because of the large spectrum of relevance of nanotechnology to the society. In November 1996, I organized a small group of researchers and experts from government including Stan Williams (Hewlett Packard), Paul Alivisatos (University of California, Berkeley) and Jim Murday (Naval Research Laboratory), and we started to do our homework in setting a vision for nanotechnology. We began with preparing supporting publications, including a report on research directions in ten areas of relevance, despite low expectation of additional funding at that moment. In 1997–1998, we ran a program solicitation 'Partnership in Nanotechnology: Functional Nanostructures' at NSF and we received feedback from the academic community. Also, we completed a worldwide study in academe, industry and governments, together with a group of experts including Richard Siegel (Rensselaer Polytechnic Institute), then at Argonne National Laboratory) and Evelyn Hu (University of California, Santa Barbara), and by the end of 1998, we had the understanding what are the possibilities at the international level. The visits performed in that time interval were essential in developing an international acceptance of nanotechnology, and defining its place among existing disciplines.

National Nanotechnology Initiative was prepared with the same rigor as a science project between 1997 and 2000: we developed a long-term vision for research and development (Roco et al., 1999), an international benchmarking of nanotechnology in academe, government and industry (Siegel et al., 1999), a plan for the US government investment (NSTC, 2000), a brochure explaining nanotechnology for the public (NSTC, 1999) and a report on the societal implication of nanoscience and nanotechnology (Roco & Bainbridge, 2001). More than 150 experts almost equally distributed between academe, industry and government contributed in setting the nanotechnology research directions, bringing in the dialog experts like Richard Smalley (Rice University), Herb Goronkin (Motorola) and Mayya Mayyappan (National Aeronautics and Space Administration (NASA) Ames).

On behalf of the interagency group, on March 11, 1999, in the historic Indian Hall at the White House's Office of Science and Technology Policy (OSTP), I proposed the NNI with a budget half billion dollars for FY 2001. While other topics were on the agenda of that meeting, nanotechnology captured the imagination of those present and discussions reverberated for about 2 h. It was the first time that a forum at this level with representatives from the major Federal R&D departments reached a decision to consider exploration of nanotechnology as a national priority. In parallel, over two dozen of other competing topics were under consideration by OSTP for priority in funding in FY 2001. We had the attention of Neil Lane, then the Presidential Science Advisor, and Tom Kalil, then economic assistant to the President.

After that presentation, our focus changed. Because nanotechnology was not known to Congress or the Administration, establishing a clear definition of nanotechnology and communicating the vision to large communities and organizations took the center stage. Indeed, the period from March 1999 through the end of the year was a time of very intense activity. Few experts gave even a small chance to nanotechnology for special funding by the White House. Nevertheless, with this proposal and the 'homework' of studies completed, we focused our attention on the six major Federal department and agencies – the National Science Foundation (NSF), Department of Defense, Department of Energy (DOE), NASA, National Institutes of Health (NIH) and the National Institute of Standards and Technology – that would place nanotechnology as a top priority during the summer of 1999.

Then, the approval process moved to Office of Management and Budget (OMB), Presidential Council of Advisors in Science and Technology (PCAST) and the Executive Office of the President (EOP, White House), and had supporting hearings in the House and Senate of the US Congress.

In November 1999, the OMB recommended nanotechnology as the only new R&D initiative for FY 2001. On December 14, 1999, the PCAST highly recommended that the President fund nanotechnology R&D. Thereafter, it was a quiet month – we had been advised by the EOP to restrain from speaking to the media about the topic because a White House announcement would be made. We prepared a draft statement. A video was being produced for the planned multimedia presentation, but we did not have time to complete it.

President Clinton announced the NNI at Caltech in January 2000 beginning with words such as 'Imagine what could be done . . .'. He used only slides. After that speech, we moved firmly in preparing the Federal plan for R&D investment, to identify the key opportunities and convincing potential contributors to be proactive. A House and then Senate hearings brought the needed recognition and feedback from Congress.

In August 2000, the White House advanced the Interagency Working Group on Nanoscience, Engineering and Technology to the level of subcommittee on Nanoscale Science, Engineering and Technology (NSET) with the charge of implementing NNI. The National Nanotechnology Coordinating Office (NNCO) was established as a secretariat office to NSET in January 2001. In the first year, the six agencies of the NNI invested about $470 million, only few percentage points less than the tentative budget proposed on March 11, 1999. In FYs 2002 and 2003, NNI has increased significantly, from 6 to 16 departments and agencies. The Presidential announcement of NNI with its vision and program motivated and partially stimulated the international community. About other 40 countries have announced priority nanotechnology programs since the NNI announcement. It was as if nanotechnology had gone through a phase transition: what had once been perceived as blue sky research of limited interest (or in the view of several groups, science fiction, or even pseudoscience), was now being seen as a key technology of the 21st century. The Bush Administration has increased the support for NNI.

After initially passing the House with a vote of 405-19 (H.R. 766), and then the Senate with unanimous support (S. 189) in November 2003, the '21st Century Nanotechnology R&D Act' was signed by the President Bush on December 3. Through this Act, Congress recognizes nanotechnology as a key challenge for the future of US in the 21st century. This Bill will stimulate not only R&D but also industrial and venture funding, education and public awareness, and states investments.

I see nanotechnology as a key national 'competency' (capability) helping existing industry to become more efficient and competitive, advancing knowledge and emerging technologies, and developing unprecedented products and medical procedures that could not be realized with existing knowledge and tools. It is a personal satisfaction to envision the immense impact that nanotechnology will have on the economy and society. Because of its far reaching implications, I see this legislation as having high societal return on public investment. In the 2003 Senate briefings, John Marburger, the Director of OSTP, has used nanotechnology as an example of national R&D endeavor with multiagency collaboration. Also, the previous Administration identified nanotechnology as an example for interagency partnership. I recall when Newt Gingrich congratulated the previous Administration for the NNI during the Societal Implications workshop held at NSF in September 2000. I trust that the bi-partisan support will continue because the nanotechnology progress is seen as 'a higher purpose' beyond party affiliation. I have devoted time for the nanotechnology advancement and NNI beyond my personal research since 1991. The credible promise that nanotechnology will change the economy and quality of life, with the recognition of the NNI from Congress and the President, is the best reward.

Besides products, tools, and healthcare, nanotechnology also implies learning, imagination, infrastructure, inventions, public acceptance, culture, anticipatory laws, and architecture of other factors. In 1997–2000, we developed a transforming plan, and in the first 3 years, 2001–2003, the vision has become a R&D reality. A main reason for the development of NNI has been the focus on intellectual drive toward exploiting new phenomena and processes, developing a unified science and engineering platform from the nanoscale, and using the molecular and nanoscale interactions for efficient manufacturing. Another main reason has been the promise of broad societal implications, including $1 trillion per year worldwide by 2015 of products where nanotechnology plays a key role, which would require 2 million workers. These estimations made in 1999 have been based on direct contacts with leading experts in large companies with related R&D programs in US, Japan, and Europe, and the international study completed between 1997 and 1999. While such estimations were received with surprise until 2001, they have become accepted by various forecasting groups in 2003 and a reference for investment decisions made by industry and governments. New estimations made in 2003 would indicate that several targets estimated to be achieved in 2015 would be reached sooner. For example, revenues from semiconductors using nanotechnology would reach $300 billion worldwide in 2010 instead of 2015 (Figure 1).

Results of the NNI investment

There are major outcomes after the first 3 years (FYs 2001–2003) of the NNI. The NNI has already created a nanoscale science and engineering 'power house' of discoveries and inventions in the US with about 40,000 researchers, students and workers qualified at least in one aspect of nanotechnology. The R&D landscape for nanotechnology research and education has changed, advancing from questions such as 'what is nanotechnology?' and 'could it ever be developed?' to 'how can we take advantage of it faster?' and 'who is the leader?' Also, the international context changed: the worldwide government investments have increased in excess of three times in 3 years, from about $825 million in 2000 (of which $270 million was in the US) to about $3 billion in 2003 (of which $862 million was in the US).

- First, research is advancing toward systematic control of matter at the nanoscale faster than envisioned in 2000, when NNI was introduced with words like 'Imagine what could be done . . . 20–30 years from now.' After 3 years, in 2003, the NNI supports about 2500 active awards in about 300 academic organizations and about 200 small businesses and non-profit organizations in all 50 states. The time of reaching commercial prototypes has been reduced by at least of factor of two for key applications such as detection of cancer, molecular electronics, and special nanocomposites.
- Second, systemic changes are in preparation for education, by earlier introduction of nanoscience

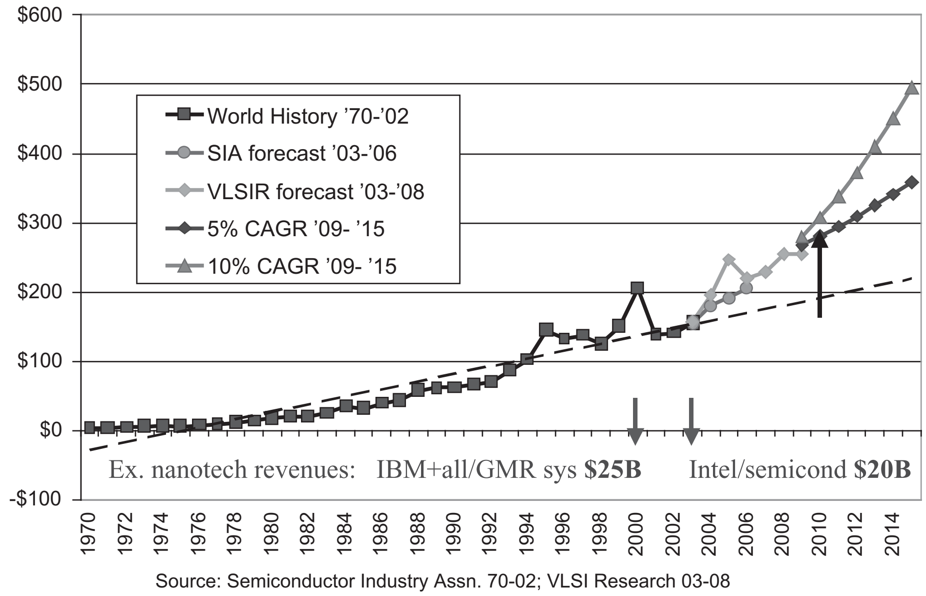

Figure 1. $300B nanotechnology revenues from semiconductors will be reached sooner than predicted (2010 instead of 2015) (The curve revenues vs. year, courtesy of SRC).

and reversing the 'pyramid of science' with understanding of the unity of nature at the nanoscale from the beginning. In 2002, NSF announced the nanotechnology undergraduate education program, and in 2003, the nanotechnology high school education program. In the next years, we plan to change the language of science even earlier and involve science museums to seed that language to K-12 students. About 7000 students and teachers have been trained in 2003 with NSF support. All major science and engineering colleges in US have introduced courses related to nanoscale science and engineering in the last 3 years.

- Third, significant infrastructure has been established in over 60 universities with nanotechnology user capabilities. Five networks (Network for Computational Nanotechnology, National Nanotechnology Infrastructure Network, Oklahoma Network for Nanotechnology, the DOE large facilities network, and the NASA nanotechnology academic centers) have been established.
- Fourth, industry investment has reached about the same level as the NNI in the medium and long-term R&D, and almost all major companies in traditional and emerging fields have nanotechnology groups at least to survey the competition. For example, Intel has reported $20 billion revenues from nanotechnology in 2003. About 75% of patents (about 6400 of 8500) related to nanotechnology as recorded by the US Patent and Trade Office in 2002 are from US while the NNI funding is about 25% of the world government investment (about $0.77B of $3.0B). About 75% of startup companies in nanotechnology in second part of 2003 are in US (about 1100 of 1500 worldwide, according to NanoBusiness Alliance). Despite the general economic downturn, nanotechnology venture funding in US doubled in 2002 as compared to 2001, and in US there are more start-up companies than all other countries combined. The NNI needs to further encourage small businesses. For example, NSF supported more than 100 small businesses with an investment of $36 million between 2001 and 2003.
- Fifth, the NNI's vision of a 'grand coalition' of academe, government, industry and professional groups is taking shape. Over 22 regional alliances have been established throughout US and develop local partnerships, support commercialization and education. Professional societies have established specialized divisions, organize workshops and continuing education programs, among them the American Association for the Advancement of Science, American Chemical Society, American Physics Society, Materials Research Society, American Society of Mechanical Engineers,

American Institute of Chemical Engineers, Institute of Electrical and Electronics Engineers, and American Vacuum Society. The FY 2004 NNI investment is over three times the corresponding Federal Investment in FY 2000 ($850 million from $270 million), and the attention is extending to the legislative and even judiciary branches of US Government.

- Sixth, societal implications were addressed from the start of the NNI, beginning with the first research and education program on environmental and societal implications, issued by NSF in July 2000. In September 2000, the report on 'Societal Implications of Nanoscience and Nanotechnology' was issued. Today, in 2003, the number of projects in the area has grown significantly, funded by NSF, EPA, NIH, DOE, and other agencies. Awareness of potential unexpected consequences of nanotechnology has increased, and Federal agencies meet periodically to discuss those issues.

Where is the NNI going from here?

Nanotechnology has the potential to change our comprehension of nature and life, develop unprecedented manufacturing tools and medical procedures, and even influence societal and international relations. The first set of nanotechnology grand challenges was established in 1999–2000, and NSET plans to update it in 2004. Lets imagine again what could be done. Here are ten potential developments by 2015 (Figure 2):

- *Half of the newly designed advanced materials and manufacturing processes are built using control at the nanoscale.* Even if this control may be rudimentary in 2015 as compared to the long-term potential of nanotechnology, this will mark a milestone toward the new industrial revolution as outlined in 2000. This estimation is based on evaluations made with industry in a variety of sectors including electronics, chemicals, heavy industry, pharmaceutical and aeronautics. By extending the experience with information technology in the 1990s, one would estimate an overall increase of social productivity by at least 1% per year because of these changes.

Ahead are several challenges. Visualization and numerical simulation of three-dimensional domains with nanometer resolution will be necessary for engineering

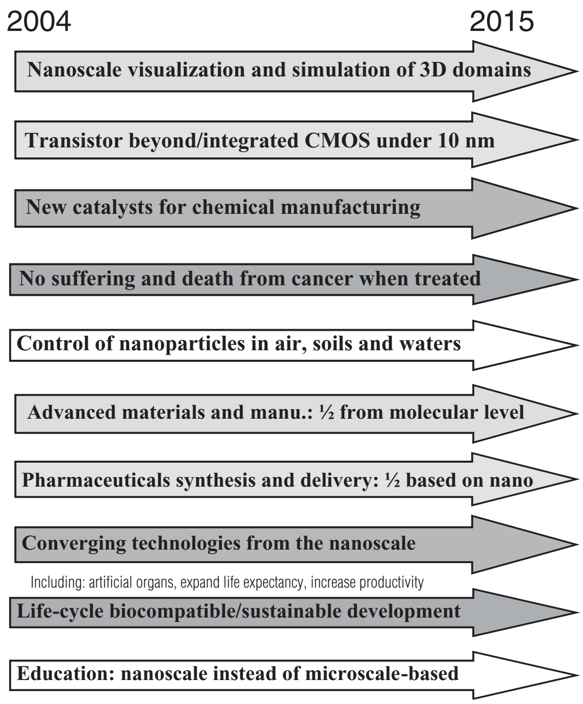

Figure 2. Ten R&D potential targets for 2015.

applications. Nanoscale designed catalysts will expand the use in 'exact' chemical manufacturing to cut and link molecular assemblies, with minimal waste. Silicon transistors will reach dimensions smaller than 10 nm and will be integrated with molecular or other kind of nanoscale systems (beyond or integrated with CMOS). Changing our goals and strategies in this area is the experimental proof of concept, completed in 2003, which showed that CMOS can work at the 5 nm gate length (and potentially at a smaller scale). One may recall that in 2000, we contemplated the 'brick wall' of physical principles that would limit the advancement of silicon technology by the end of this decade. Now we are looking to advances in CMOS technology to extend another decade (by 2020) and then to its integration with bottom-up molecular assembling. As nanoscale science and engineering advances, nanomanufacturing will evolve from creating passive and active nanoscale materials and devices (what we begin to do now) to creating three-dimensional nanosystems with new architecutures and developing molecular assemblies with new atomic and molecular configurations "by design".

- *Suffering from chronic illnesses is being sharply reduced.* It is conceivable that by 2015, our ability to detect and treat tumors in their first year of occurrence might totally eliminate suffering and death from cancer. In 2000, we aimed for earlier detection of cancer within 20–30 years. Today, based on the results obtained during 2001–2003 in understanding the processes within a cell and new instrumentation to characterize those cellular processes, we are trying to eliminate cancer as a cause of death if treated in a timely manner. Pharmaceutical synthesis, processing, and delivery will be enhanced by nanoscale control, and about half of pharmaceuticals will use nanotechnology in a key component. Modeling the brain based on neuron-to-neuron interactions will be possible by using advances in nanoscale measurement and simulation.
- *Converging technologies from the nanoscale will establish a mainstream pattern for applying and integrating nanotechnology with biology, electronics, medicine, learning and other fields.* It includes hybrid manufacturing, neuromorphic engineering, artificial organs, expanding life span, enhancing learning, and sensorial capacities. New concepts in distributed manufacturing and multicompetency clustering will be developed.
- *Life-cycle sustainability and biocompatibility will be pursued in the development of new products.* Knowledge development in nanotechnology will lead to reliable safety rules for limiting unexpected environmental and health consequences of nanostructures. Synergism among life-cycles of various groups of products will be introduced for overall sustainable development. Control of contents of nanoparticles will be performed in air, soils, and waters using a national network.
- *Knowledge development and education will originate from the nanoscale instead of the microscale.* Earlier nanoscience education will change the role of science and motivation for schoolchildren. A new education paradigm not based on disciplines but on unity of nature and education–research integration will be tested for K-16 (reversing the pyramid of learning (Roco, October 2003). Science and education paradigm changes will be at least as fundamental as those during the 'microscale S&E transition' that originated in 1950s where microscale analysis and scientific analysis were stimulated by the space race and digital revolution. The new 'nanoscale S&E transition' will change the foundation of analysis and the language of education stimulated by the nanotechnology products. This new 'transition' originated at the threshold of the third millennium.
- *Nanotechnology businesses and organizations will restructure toward integration with other technologies, distributed production, continuing education, and forming consortia of complementary activities.* Traditional and emerging technologies will be equally affected.

Responsible development of nanotechnology

A main reason for developing nanotechnology is to extend the limits of sustainable development. One way is 'exact' manufacturing at the nanoscale with small consumption of energy, water, and materials, as well as minimized waste. Another way is reducing the effects of existing nanostructured contaminants from traditional activities such as combustion engines or from natural sources such as biomineralization and sediment fragmentation. Third is controlling the evolution of existing and newly released nanostructures in the environment. The NNI annual investment in nanoscale research with relevance to environment is estimated at about $50 million in 2002, of which NSF awards about $30 million and EPA awards about $6 million. If one would add the research for societal and educational implications, the investment is about 10% of the total annual NNI budget.

All material stuff around us, either natural or manmade, has a structure at the nanoscale. All living cells interact with nanostructures when they feed, breed, or are touched by viruses. Developing knowledge at the nanoscale is a natural trend in science and engineering. This may prepare us to address unexpected risks of human activity such as encountering unknown viruses and bacteria. Nanotechnology activities may rise additional challenges because of nanostructures may have more reactive surfaces and exhibit new functions for the same chemical composition.

National Nanotechnology Initiative research is developing new knowledge for such issues in more than 120 projects at the end of 2003, including several centers at the University of California, Davis (nanoparticles in the environment), Worcester Polytechnic Institute (air pollution), University of Illinois at Urbana (water purification), Rice University (nanostructures in the environment), and University of Notre Dame (nanoparticles in soils). Questions researchers are addressing are: what is different for artificially created nanostructures? and how would those nanostructures behave differently if released in the environment? Nanotechnology will develop in the areas where potential advantages would exceed the impact of potential risks, and where the potential risks are limited and can be addressed. Current approaches show that nanotechnology consequences in research or production are best addressed within the existing system applications such as biology, chemistry or electronics.

Key questions asked by technology users and the public are about economic development and commercialization, education, infrastructure, environmental, health, ethical, and legal aspects. We have the responsibility to increase productivity, better use natural resources, reduce poverty and hunger, improve health care, and enhance human resources as well as to address health and environmental risks and related efforts to reduce them. The response must be balanced. Considering the opinions of individual groups – at times different from the largest majority and sometimes conflicting with scientific facts – needs to be done in the context of broader societal goals.

The vision of few nanometer intelligent robots mentioned in science fiction literature (see the novel 'Prey' by M. Crichton) leads to immediate criticism by some groups that are concerned that such robots would take over the world and damage the environment. This dialogue is carried out, ignoring input from researchers who note that basic laws of mass and energy conservation may not lead to infinitely multiplying material objects, and that only a complex system of already known living systems may multiply and be intelligent.

Our role is to provide R&D support for knowledge development, identify possible risks for health, environment, and human dignity, and inform the public with a balanced approach about the benefits and potential unexpected consequences.

The NSF prepared a report on 'Societal Implications of Nanoscience and Nanotechnology' in September 2000 and published it for broader public distribution in 2001 (Roco & Bainbridge, 2001). The proceedings were followed by various program solicitations and the assignment to the NNCO in 2001, of a monitoring role for potential risks. The NNCO also has the role to communicate with the public and address unexpected consequences. As a follow-up to that report, NSF has made support for social, ethical, and economic research studies a priority by (a) including it as a new theme in the NSF annual program solicitations since 2000; (b) contributions in the research and education centers; and (c) conducting a study on the impact of technology and converging technologies from the nanoscale (Roco & Bainbridge, 2002).

National Science Foundation has pursued the research and education themes 'Nanoscale processes in the environment' and 'Societal and Educational Implications of Nanotechnology' as part of its NNI programs since July 2000 (annual program solicitations NSF 00-119, 01-157, 02-148, 03-043; 03-044), and 100 examples of awards made in this area are posted on www.nsf.gov/nano (click on Solicitations and Outcomes). EPA has had annual program announcements in the STAR program with focus on nanotechnology and environment since 2002; in FY 2003, 22 awards were made and about 12, in 2004. DOE has included nanoscience in environmental research performed at several National Laboratories such as Oak Ridge in Tennessee and Environmental Molecular Laboratory in Washington State. Additional SBIR/STTR awards were made at NSF after 1999 when nanotechnology was specifically targeted in the respective program announcements. EPA will have an SBIR solicitation on 'Nanomaterials and Clean Technology' with a deadline in May 2004. FDA, EPA, and other regulatory agencies are following very closely the research results.

The NNI annual investment in research and educational with relevance to environment has increased progressively since 2000. Other programs dedicated to environmental implications of nanotechnology abroad were announced in March 2003 by European Community and in November 2003 by Taiwan, about 3 years after the NSF first called for proposals in that area.

One should not sidetrack the efforts for sustainable development by delaying or halting the creation of new knowledge in the field. At the international 'Nanotech 2003 and Future' conference in Japan on February 26, 2003, during my keynote address, I made an international appeal to researchers and funding organizations 'to take timely and responsible advantage of the new technology for economic and sustainable development, to initiate societal implications studies from the beginning of the nanotechnology programs, and to communicate effectively the goals and potential risks with research users and the public' (Roco, July 2003). Since then, I have had discussions with representatives from EC, APEC, Switzerland, UK, Taiwan, China, Australia, and other countries about this topic. International collaboration is necessary in a field that does not have borders, where the products are sold internationally, and the health and environmental aspects are of general interest.

Nanotechnology is still in the precompetitive phase in most areas of relevance and international collaboration is beneficial. Nanotechnology has the long-term potential to bring revolutionary changes in society and harmonize international efforts toward a higher purpose than just advancing a single field of science and technology, or a single geographical region. A global strategy guided by broad societal goals of mutual interest is envisioned.

How did you get involved with nanotechnology?

I have been captivated by the unity and coherence encountered in nature. I believe that a corresponding coherence must be reflected in the research and education endeavor. In my own academic research on multiphase systems in the earlier 1980s, during a NSF sponsored project at the University of Kentucky, I noted that the transition from single molecules to continuum behavior causes functional changes that cannot be explained with microscale models, no matter the phase – solid, liquid, gas, or plasma. In a subsequent IBM-sponsored project on two-phase toner flow, I observed how nanometer-size particles and thin layers unexpectedly and significantly change properties if their dimensions or shapes were changed by less than the atomic or molecular size. For example, a confined nanolayer may transit from superfluid to quasi-solid behavior if its thickness changes with less than one molecular diameter. Interactions with numerous researchers, consulting with a variety of industries, and visiting professorships at Caltech, Tohoku University, and Delft University revealed to me many other facets and also the common treads of nanoscience.

I came to NSF in 1990 as a program director (although I maintained my university position until 1995) because I was interested in the 'big picture,' and wanted to promote the coherence of science and technology – and also because I had several specific ideas on nanotechnology and academe–industry interaction. In 1990, I proposed that NSF fund a new emerging technology program on 'nanoparticle synthesis and processing at high rates.' This was awarded at about $3 million in 1991, leading to the first government program with emphasis on 'nano'.

In an interview with Business Week in August 1991, I concluded that it might take '5–10 years' for the field to be recognized. One reason was that the nanoscale behavior could not be easily measured, simulated, or controlled. Also, each discipline had its own principles, and it was not clear at that time that the several phenomena would dominate nanoscale no matter the field of relevance, or that the weak molecular interactions could be exploited for efficient manufacturing. Nonetheless, I kept on taking time for nanotechnology in addition to my other core duties at NSF – sometimes without any assurance that I would be able to continue working in that direction. I had become convinced that the discovery and mastery of this intermediate length scale, running from the width of a single atom or molecule to about 100 molecular diameters, would be a historical event in science and engineering. It is here that we find the transition between the discontinuous behavior of atoms and molecules, and the continuous macroscopic properties of matter that we can detect with our senses. The first level of organization of atoms and molecules is established in this length range. It is here that we find the transition between inert chemicals and life. This is where all the fundamental structures and properties of matter are defined, and can be changed with small energy consumption by rearranging the material structure. Here we can use the 'weak' molecular interactions to yield the most efficient manufacturing methods. This is the domain of confluence of exact science of few atoms on one side, and technology of assembling them into useful products on the other side. This is the lowest scale where we can transform matter under control for practical purposes.

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See also www.nano.gov and www.nsf.gov/nano

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